

# Atomizing-Gas Temperature Effect on Cryogenic Spray Dropsizes

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# ATOMIZING-GAS TEMPERATURE EFFECT ON CRYOGENIC SPRAY DROPSIZE

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## Abstract

Correlating expressions for two-phase flow breakup of liquid nitrogen,  $LN_2$ , jets in sonic velocity nitrogen gasflows were obtained for an atomizing-gas temperature range of 111 to 442 K. The correlations were based on characteristic dropsizes measurements obtained with a scattered-light scanner. The effect of droplet vaporization on the measurements of the volume-median dropsizes,  $D_{v.5}$ , was calculated by using previously determined heat and momentum transfer expressions for droplets evaporating in high-velocity gasflow. Finally, the dropsizes of the originally unvaporized spray,  $D_{v.5c}$ , was calculated, normalized with respect to jet diameter,  $D_o$ , and correlated with atomizing-gas flowrate and temperature, according to the following expression:

$$\frac{D_o}{D_{v.5c}} = 9.0 \left( WeRe \frac{\rho_g}{\rho_l} \right)^{0.44} \left( \frac{t_g}{t_o} \right)^{1.25}$$

where  $WeRe = \rho_g^2 D_o^2 V_c^3 / \mu_l \sigma$ . Here  $\mu_l$  is liquid viscosity,  $\rho_g$  and  $\rho_l$  are gas and liquid densities, respectively,  $\sigma$  is surface tension,  $V_c$  is acoustic gas velocity and  $T_g$  is atomizing-gas temperature, normalized with respect to airstream temperature,  $T_o = 293$  K. This expression agrees well with atomization theory which predicts  $D_{v.5} \sim V_c^{1.33}$ , for liquid-jet breakup in high-velocity gasflow.

## Nomenclature

$A_o$	fuel nozzle orifice area, $cm^2$
$a$	acceleration, $cm/sec^2$
$C_d$	drag coefficient
$D_o$	liquid-jet diameter, $cm$
$D_{v.5}$	volume median drop diameter, $cm$
$k$	correlation coefficient for Eq. (1)
$k'$	correlation coefficient for Eq. (6)
$k''$	correlation coefficient for Eq. (7)
$Nu$	heat-transfer Nusselt number, based on $D_{v.5e}$
$n$	exponent for Eq. (1)

$Re$	Reynolds number based on $D_{v.5e}$
$t$	vaporization time, $sec$
$V_c$	acoustic velocity, $cm/sec$
$W$	weight flow of fluid, $g/sec$
$We$	Weber number based on $D_{v.5e}$
$x$	axial downstream spray sampling distance
$\sigma$	surface tension relative to air, $dynes/cm$
$\mu$	absolute viscosity, $g/cm \ sec$
$\rho$	fluid density, $g/cm^3$

## Subscripts

$c$	calculated
$d$	droplet
$e$	experimental
$f$	free-stream
$g$	gaseous nitrogen, $GN_2$
$l$	liquid nitrogen, $LN_2$
$o$	orifice

## Introduction

An experimental investigation of cryogenic liquid-jet breakup in high-velocity gasflow was conducted to determine the effect of atomizing-gas temperature,  $T_g$ , on characteristic dropsizes,  $D_{v.5}$ , of liquid-nitrogen sprays. Very little data are available in the spray literature that show gas-temperature effects on atomization. However, the effect of gas velocity,  $V_g$ , on liquid-jet breakup in gas streams has been studied by numerous investigators.<sup>1-7</sup> Their results are summarized in Table I. Water-jet breakup results described in Ref. 1 show that good agreement can be obtained with atomization theory, when dropsizes measurements are made close to the atomizer orifice. However, a marked effect of droplet vaporization on dropsizes measurements of water sprays did occur, as reported in Ref. 1, when the sampling distance downstream of the atomizer was increased from 2.2 to 6.7  $cm$ . In the case of liquid-nitrogen sprays, good agreement with atomization theory may not occur, since highly volatile sprays can quickly become partially vaporized.

In a previous investigation of disintegrating  $\text{LN}_2$  jets,<sup>2</sup> dropsize measurements were made in the presence of relatively high thermal gradients. The atomizing gas,  $\text{GN}_2$ , was at room temperature, 293 K, whereas  $\text{LN}_2$  droplet temperatures were near the boiling point of  $\text{LN}_2$ , 77 K. Thus, heat transfer across the gas film had a driving potential,  $\Delta T$ , of 216 K. This is considerably higher than values of  $\Delta T$  in the order of 10 to 15 K, which were encountered in previous water spray studies reported in Ref. 1.

Although the original characteristic dropsize initially formed at the atomizer orifice was not measured directly, in the present study, it was possible to determine the initial value of  $D_{v,5c}$  by calculating the amount it had changed due to evaporation. Droplet acceleration and vaporization rates were calculated from heat transfer and drag coefficient data given in Ref. 8. These data had previously been obtained for drops accelerating and vaporizing in high-velocity gasflows. Such data are difficult to obtain for drops that are microscopic in size and attain high velocity in a short distance of travel. By using heat transfer and drag coefficients given in Ref. 8, values of  $\Delta D_{v,5}$  produced by droplet vaporization could be calculated and used to determine original values of  $D_{v,5c}$  that existed before vaporization and occurred.

To determine the effect of atomizing-gas temperature and gas mass-flux on spray dropsize produced by liquid-jet breakup in high-velocity gasflow, the characteristic dropsize  $D_{v,5c}$  was measured with a scattered-light scanner developed at NASA Lewis Research Center by Buchele.<sup>9</sup> Sprays were sampled with the laser beam center line positioned at a distance of 1.2 cm downstream of the fuel nozzle orifice to minimize the loss of small droplets due to vaporization. Volume mean diameter,  $D_{v,5c}$  varied from 3 to 30  $\mu\text{m}$  and measurements of  $D_{v,5c}$  were made at atomizing-gas temperatures of 111, 293, and 422 K, respectively.

#### Apparatus and Procedure

A two-fluid nozzle was used with assist nitrogen gasflow,  $\text{GN}_2$ , to breakup liquid nitrogen,  $\text{LN}_2$ -jets, as shown in Fig. 1. It was mounted at the center line of the 24-cm diameter duct and operated over pressure ranges of 0.2 to 1.0 MPa for both  $\text{LN}_2$  and  $\text{GN}_2$ .  $\text{LN}_2$  sprays were injected downstream into the airflow, just upstream of the duct exit, and sampled at a distance of 1.2 cm downstream from the atomizer orifice to the center line of the  $4.4 \times 1.9$  cm laser beam. The two-fluid nozzle was fabricated according to the diagram illustrated in Fig. 2.  $\text{LN}_2$  at a temperature of 77 K was axially injected into the airstream by gradually opening the control valve until the desired flowrate of 51 g/sec was

obtained as indicated by a turbine flowmeter. The atomizing gas was then turned on and weight flowrate was measured with a 0.51-cm diameter sharp-edge orifice. After the air,  $\text{GN}_2$  and  $\text{LN}_2$  flowrates were set, the volume median diameter,  $D_{v,5c}$ , was measured with the scattered-light scanner.

The optical system of the scattered-light scanner shown in Fig. 3 consisted of a laser beam expander with spatial filter, rotating scanning-slit and a detector. The instrument measures scattered light as a function of scattering angle by repeatedly sweeping a variable-length slit in the focal plane of the collecting lens. The data obtained is scattered-light energy as a function of the scattering angle relative to the laser beam axis. This method of particle size measurement is similar to that described in Ref. 10. Measurements of scattered-light energy normalized by the maximum energy were plotted against scattering angle and used to determine volume-median diameter,  $D_{v,5c}$ , as described in Ref. 11. Also, it should be noted that the size-distribution dispersion can also be determined from this plot. Also, this method of determining characteristic dropsize and dispersion of dropsize can be used independent of particle size distribution function, according to Buchele.<sup>11</sup> For a typical measurement, the scan is repeated 60 times per second to average out any temporal variations in the energy curve.

Spray pattern effects were minimized by measuring  $D_{v,5c}$  for the entire cloud of droplets. The instrument was calibrated with five sets of monosized polystyrene spheres having diameters of 8, 12, 25, 50, and 100  $\mu\text{m}$ . Since the sprays were sampled very close to the atomizer orifice, they contained a relatively high number-density of very small droplets. As a result, the light-scattering measurements required correction for multiple scattering as described in Ref. 12. Also, dropsize measurements were corrected to include Mie scattering theory when very small drop diameters, i.e., 10  $\mu\text{m}$ , were measured. Reproducibility tests showed that experimental measurements agreed within  $\pm 5$  percent.

It was necessary to correct experimental measurements by taking background readings when the atomizing-gas,  $\text{GN}_2$  temperature was well above or below airstream temperature. This was due to high gas-density gradients being present when atomizing-gas temperatures were relatively high, 422 K, or low, 111 K, as compared with the surrounding airstream temperature of 293 K. Only a small correction was needed at  $T_g = 293$  K, since gas density gradients were close to zero. Temperature gradients for nitrogen vapor films surrounding the droplets were assumed to have negligible effect on measurements, since this was found to be the case when water sprays were studied in Ref. 15.

## Experimental Results

To obtain droplet size measurements, the entire LN<sub>2</sub>-spray cross section was sampled and the laser beam center line was located at a distance of 1.2 cm downstream of the fuel-nozzle orifice, as shown in Fig. 1. Droplets traveled a distance of 2.0 cm in passing through the scattered-light scanner laser beam. However, some of the very small and highly volatile LN<sub>2</sub> droplets were completely vaporized before they could travel through the laser beam. As a result, experimental values of  $D_{v.5e}$  were obtained for partially vaporized sprays. Thus, it was necessary to calculate the change in droplet size,  $\Delta D_{v.5}^2$ , in order to estimate the initially unvaporized spray droplet size,  $D_{v.5c}$ , that was formed at the fuel-nozzle orifice. Values of  $D_{v.5c}$  were then correlated with atomizing-gas flowrate,  $W_g$ . Such correlations are needed for modeling spray vaporization and combustion processes.

### Effect of GN<sub>2</sub> Flowrate on $D_{v.5e}$

Measurements of  $D_{v.5e}$  were made with the scattered-light scanner and plotted against GN<sub>2</sub> flowrate,  $W_g$ , as shown in Fig. 4. Since high-velocity atomizing-gas flowrates were used, cryogenic liquid-jet breakup occurred primarily in the regime of aerodynamic stripping. No indication of secondary breakup of droplets was observed since low atomizing-gas velocities were not used. Thus, the low gas-velocity regime of capillary wave breakup of liquid jets was not investigated.

From the plot shown in Fig. 4, reciprocal  $D_{v.5e}$  was correlated with atomizing-gas flowrate,  $W_g$ , and the following expression was obtained:

$$D_{v.5e}^{-1} = k_e W_g^n \quad (1)$$

Values of the proportionality constant  $k$  and exponent  $n$  are given in Table II. At an atomizing-gas temperature of 293 K, the following expression was obtained:  $D_{v.5e}^{-1} = 301 W_g^{1.11}$ , where  $D_{v.5e}^{-1}$  and  $W_g$  are expressed as cm<sup>-1</sup> and g/sec, respectively.

The exponent 1.11 for  $W_g$  is considerably less than 1.33 as predicted by theory for liquid-jet breakup in high-velocity gasflow. This discrepancy can be attributed to a loss of small vaporizing LN<sub>2</sub> drops before spray measurements could be made with the scattered-light scanner. In the present study, results agree better with atomization theory than those reported in Ref. 9. This is due to the allowance made in the present study for the effect of droplet vaporization on droplet size measurements of highly volatile sprays. This effect was not accounted for in Ref. 9 and although the droplet size data

did appear to agree with theory, the proportionality constant  $k$  was too low to adequately characterize the initial unvaporized spray. Thus, the study in Ref. 9 did not take into account the effect of small droplets vaporizing completely before they could pass through the laser beam.

### Acceleration of LN<sub>2</sub> Droplets

The effect of droplet vaporization rate on experimental values of  $D_{v.5e}$  was determined by calculating vaporization time,  $t$ , as based on droplet velocity  $V_d$ , for  $D_{v.5e}$ . Time,  $t$ , was calculated over a distance of 2.2 cm, i.e., the distance from nozzle orifice to the downstream edge of the laser beam, as shown in Fig. 3.

In order to determine volume-median drop velocity,  $V_d$ , the acceleration,  $a$ , of LN<sub>2</sub> droplets was calculated from the following momentum balance as given in Ref. 8:

$$m_d a = \frac{1}{2} \rho_g A_d (V_g - V_d)^2 C_d \quad (2)$$

where  $m_d$  and  $A_d$  are mass and area of droplet size  $D_{v.5e}$ , respectively, i.e.,  $m_d = \rho_1 \pi D_{v.5e}^3 / 6$ ,  $C_d$  is the drag coefficient based on characteristic length,  $D_{v.5e}$ . Rewriting this expression, in terms of change in drop-velocity squared,  $\Delta V_d^2$ , over the distance of travel,  $\Delta x$ , the following relationship is obtained:

$$\frac{\Delta V_d^2}{\Delta x} = \frac{3 \rho_g (V_g - V_d)^2}{2 \rho_1 D_{v.5e}} C_d \quad (3)$$

where  $C_d = 27 \text{ Re}^{0.84}$ , as given in Ref. 8, and  $\text{Re}$  is based on the characteristic droplet size,  $D_{v.5e}$ .

The deceleration of atomizing gaseous nitrogen jets into a surrounding low velocity airflow was determined as follows. At the nozzle orifice, gas velocity,  $V_g$ , was equal to the acoustic velocity,  $V_c$ , of gaseous nitrogen. Values of  $V_g$  used to solve Eq. (3), were calculated at downstream distances of  $x = 0.5$ , and 10 cm, respectively and plotted in Fig. 5. Calculated values of  $V_g^2$  are based on data given in Ref. 13 and plotted in Fig. 5 for comparison. The percent deceleration of the atomizing nitrogen gas is assumed to be approximately the same in both cases, since the two-fluid nozzles used in Ref. 13 and the present study were very similar in design.

To determine the acceleration of LN<sub>2</sub> droplets characterized by  $D_{v.5e}$ , values of  $V_d^2$  were calculated by numerically integrating Eq. (3) and plotting  $V_d^2$  against

downstream distance,  $x$ , as shown in Fig. 6, for three atomizing-gas temperatures.  $\text{LN}_2$  droplet vaporization time,  $\Delta t$ , was calculated from this plot by means of the expression  $\Delta t = \Delta x / \bar{V}_d$ . Calculated values of  $\Delta t$  for a given distance  $\Delta x$  are given in Table III along with calculated Reynolds numbers averaged over the incremental distance  $\Delta x$  and values of  $D_{v.5c}$ . Gas and liquid transport properties used in calculating vaporization times are given in Table IV.

### Cryogenic Spray Vaporization Rates

Vaporization rates of  $\text{LN}_2$  sprays characterized by  $D_{v.5e}$  were calculated by using the following heat-balance equation:  $dm_d/dt = hA \Delta T/H_t$ , where  $h$  is the heat-transfer coefficient,  $A$  is droplet surface-area based on  $D_{v.5e}$ ,  $\Delta T = T_g - T_d$ , and  $H_t = H_v + C_p \Delta T$ . Here  $H_v$  is the latent heat of vaporization of  $\text{LN}_2$  and  $C_p$  is the specific heat of  $\text{GN}_2$ . This expression may be rewritten as follows to obtain vaporization rate in terms of changes in droplet surface-area with time:

$$\frac{\Delta D_{v.5}^2}{\Delta t} = \frac{4k_g \Delta T \text{Nu}}{\rho_l H_t} \quad (4)$$

where  $k_g$  and  $\rho_l$  are gas thermal conductivity and liquid density, respectively. In previous fuel droplet studies reported in Ref. 8, a high-speed droplet tracking camera was used to determine vaporization rates of fuels such as n-octane, jet-A, and numerous other liquids including water, benzene, acetone, and carbon tetrachloride. It was found that:  $\text{Nu} = 2 + 0.303 \text{Re}^{0.6}$ , where  $\text{Re} = \rho_g D_{v.5e} \Delta V / \mu_g$ , and  $\Delta V$  is the average velocity difference over an incremental distance  $\Delta x$ . Vaporization rate calculations were based on the characteristic drop diameter  $D_{v.5e}$ .  $\text{GN}_2$  viscosity and thermal conductivity were evaluated at the average gas-film temperature, i.e.,  $T_f = 1/2 (T_g + T_1)$ .  $\text{LN}_2$  droplet surface temperatures were assumed to be near the boiling point, 77 K, when droplet sprays were being accelerated and partially vaporized. The latent heat of vaporization of  $\text{LN}_2$  was evaluated at 77 K and the specific heat of nitrogen vapor was evaluated at the average gas-film temperature,  $T_f$ .

Experimental values of  $D_{v.5e}^{-1}$ , calculated values of  $D_{v.5c}^{-1}$  and changes in characteristic drop diameter squared,  $\Delta D_{v.5}^2$ , that occurred due to partial vaporization of the cryogenic sprays are given in Table V. Calculations were based on  $\text{GN}_2$  and  $\text{LN}_2$  flowrates of 4.54 and 51 g/sec, respectively. Values of  $D_{v.5c}$  were calculated from the expression:  $-\Delta D_{v.5}^2 = D_{v.5c}^2 - D_{v.5e}^2$  and they are plotted against  $W_g$  as shown in Fig. 7.

From this plot, the following correlating expression is obtained:  $D_{v.5c}^{-1} = k_c W_g^n$ , which is similar to Eq. (1). Values of  $k_c$  and  $n$  are given in Table V. For the case  $T_g = 293 \text{ K}$ :

$$D_{v.5c}^{-1} = 285 W_g^{1.33} \quad (5)$$

Comparing this expression with Eq. (1), i.e.,  $D_{v.5e}^{-1} = 301 W_g^{1.11}$ , shows that the proportionality constants  $k_e$  and  $k_c$  are nearly equal. Also, Eq. (5) shows that droplet vaporization did have considerable effect on the exponent  $n$ . The value of  $n$  given in Eq. (5) agrees well with atomization theory which predicts  $n = 1.33$ . Thus, the agreement of Eq. (5) with atomization theory indicates that an expression for the unvaporized spray near the fuel-nozzle orifice can be calculated using heat-transfer and drag coefficients given in Ref. 8.

### Correlation of $D_{v.5c}$ with Dimensionless Force Ratios

The calculated volume-median diameter  $D_{v.5c}$  was normalized with respect to  $\text{LN}_2$  jet diameter,  $D_o$ , and as shown in Fig. 8, is plotted against the product of  $\text{We}$ ,  $\text{Re}$ , and  $\rho_g/\rho_l$ , i.e., the Weber number, Reynolds number, and gas-to-liquid density ratio, respectively. From this plot, the following dimensionless expression was derived:

$$\frac{D_o}{D_{v.5c}} = k'_c \left( \text{WeRe} \frac{\rho_g}{\rho_l} \right)^{0.44} \quad (6)$$

where  $\text{WeRe}$  is the ratio of aerodynamic to liquid-jet surface forces, i.e., liquid viscosity and surface tension. From the three plots shown in Fig. 8, it is evident that  $D_{v.5c}$  is a function of atomizing-gas temperature, i.e.,  $D_o/D_{v.5c} = f(T_g)$ . Thus,  $k'_c$  is assumed to be a function of atomizing-gas temperature normalized with respect to  $T_f$ , i.e.,  $k'_c \sim T_g/T_f$ , where  $T_f$  is the free-airstream temperature, 293 K, of the low velocity airflow in the test section as shown in Fig. 1.

From a log-log plot of  $k'_c$  against  $T_g/T_f$  it was found that  $k'_c \sim (T_g/T_f)^{1.25}$  and as a result, the following correlating expression can be written:

$$\frac{D_o}{D_{v.5c}} = k_c'' \left( \text{WeRe} \frac{\rho_g}{\rho_l} \right)^{0.44} \left( \frac{T_g}{T_f} \right)^{1.25} \quad (7)$$

This expression is plotted in Fig. 9 which shows that  $k_c'' = 9.0$ . Thus, Eq. (7) may be rewritten as follows:

$$D_{v,5c}^{-1} = \frac{9}{D_o} \left( \frac{D_o^2}{\rho_1 \mu_1 \sigma} \right)^{0.44} (\rho_g V_c)^{1.33} \left( \frac{T_g}{T_f} \right)^{1.25} \quad (8)$$

where  $\rho_g V_c = W_g/A_o$ . Here it is evident that the thermodynamic effect of normalized atomizing-gas temperature,  $T_g/T_f$  on the reciprocal volume-median diameter is nearly as great as that of the atomizing-gas mass flux  $\rho_g V_c$ , which is also a function of gas temperature, i.e.,  $\rho_g V_c \sim T_g^{-0.5}$ . As a result, Eq. (8) shows that  $D_{v,5c}^{-1} \sim T_g^{0.58}$ . A similar effect of atomizing-gas temperature on  $D_{v,5}$  was obtained for water sprays, as reported in Ref. 15.

From experimental droplet size measurements of partially vaporized liquid-nitrogen sprays, it was found that increasing the atomizing-gas temperature gave a marked increase in the surface area per unit volume of liquid-nitrogen sprays. A result that would be very beneficial in producing very rapid and efficient fuel-spray combustion in gas turbine and rocket combustors.

### Concluding Remarks

Computations in the present study were based on numerical integration of momentum and heat-transfer expressions that had been developed in previous droplet studies, at NASA Lewis. As a result, the effect of droplet vaporization on droplet size measurements was determined. Without this source of knowledge, on calculating rates of heat and momentum transfer to vaporizing cryogenic drops, it would be almost impossible to determine the characteristic droplet size of an initially unvaporized cryogenic spray produced at the orifice of a two-fluid fuel nozzle. Thus with the computational method used in this study, it was possible to determine the effect of atomizing-gas temperature on cryogenic spray droplet size, once the effect of droplet vaporization on droplet size measurements had been determined. Also, it was found that the effect of atomizing-gas mass-flux,  $\rho_g V_c$ , on volume-median drop diameter agreed well with atomization theory for liquid-jet breakup in high-velocity gasflows. The final correlating expression derived in this study (Eq. (8)), can be readily applied to analytical modeling of fuel spray vaporization and combustion in gas-turbine and rocket combustors, within the range of variables investigated in this study.

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TABLE I.—ATOMIZING-GAS VELOCITY EXPONENT,  $n$ , FOR HIGH-VELOCITY GASFLOW BREAKUP OF LIQUID JETS

Source	Exponent, $n$
Adelberg, Theory <sup>14</sup>	1.33
Present study, $x = 2.2$ cm	1.33
Kim and Marshall <sup>3</sup>	1.14
Lorenzetto and Lefebvre <sup>4</sup>	1.00
Nukiyama and Tanasawa, <sup>5</sup> $x = 5$ to 25 cm	1.00
Weiss and Worsham <sup>6</sup>	1.33
Wolf and Anderson <sup>7</sup>	1.33

TABLE II.—COEFFICIENT  $k$  AND EXPONENT  $n$  FOR EQ. (1)<sup>a</sup>

Atomizing-gas temperature, $T_g$ , K	$k$	$n$
111	82	1.22
293	301	1.11
422	367	1.08

$$^a D_{v.5e}^{-1} = k_g W_g^n$$

TABLE III.—VAPORIZATION TIME,  $t$ , FOR  $D_{v.5e}^{-1}$  AT  $W_g = 4.54$  g/sec AND  $\Delta x = 2.2$  cm

Atomizing-gas temperature, $T_g$ , K	$D_{v.5e}^{-1}$ , $\text{cm}^{-1}$	$\Delta t \times 10^4$ , sec
111	540	4.40
293	1600	1.44
422	1900	.99



TABLE IV.—GN<sub>2</sub> AND LN<sub>2</sub> TRANSPORT PROPERTIES AT $W_g = 4.54 \text{ g/sec}$  AND  $T_g = 293 \text{ K}$ 

<u>Nitrogen gas</u>	
$V_c$ , cm/sec .....	$3.43 \times 10^4$
$\rho_g$ , g/cc .....	$3.84 \times 10^{-4}$
$\mu_g$ , g/cm sec .....	$1.25 \times 10^{-4}$
$k_g$ , cal/sec sq cm ( $^{\circ}\text{C}/\text{cm}$ ) .....	$4.20 \times 10^{-5}$
<u>LN<sub>2</sub> droplets</u>	
$V_d$ , cm/sec .....	204
$\rho_l$ , g/cc .....	0.80
$H_v$ , cal/g .....	47.8
$C_{pv}$ , cal/g $^{\circ}\text{C}$ .....	0.25

\*Evaluated at  $T_f = 1/2(T_g - T_1)$ .TABLE V.—REDUCTION IN DROPSIZE,  $-\Delta D_{v,5}^2$ , AND  
UNVAPORIZED DROPSIZE,  $D_{v,5}$ , AT  $W_g = 4.54 \text{ g/sec}$ 

Atomizing-gas temperature, $T_g$ , K	$-\Delta D_{v,5}^2 \times 10^9$ , $\text{cm}^2$	$D_{v,5}^{-1}$ , $\text{cm}^{-1}$	$D_{v,5c}^{-1}$ , $\text{cm}^{-1}$
111	29.7	540	565
293	16.3	1600	2100
422	13.2	2000	2950

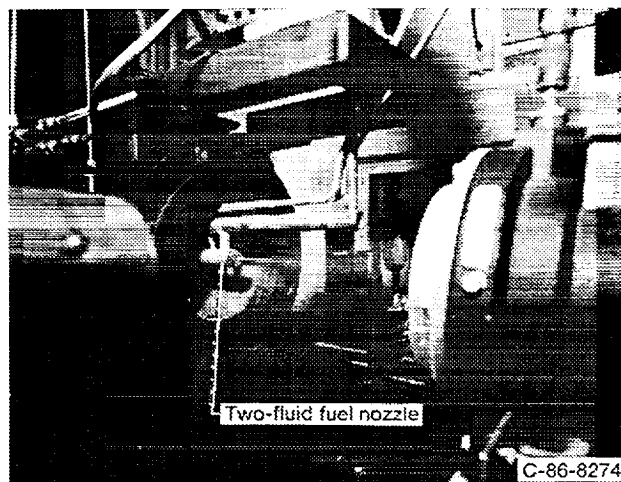


Figure 1.—Apparatus and auxiliary equipment.

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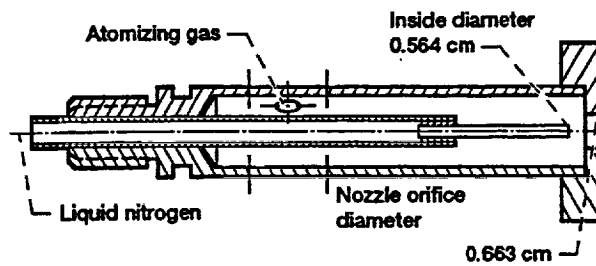


Figure 2.—Diagram of pneumatic two-fluid atomizer.

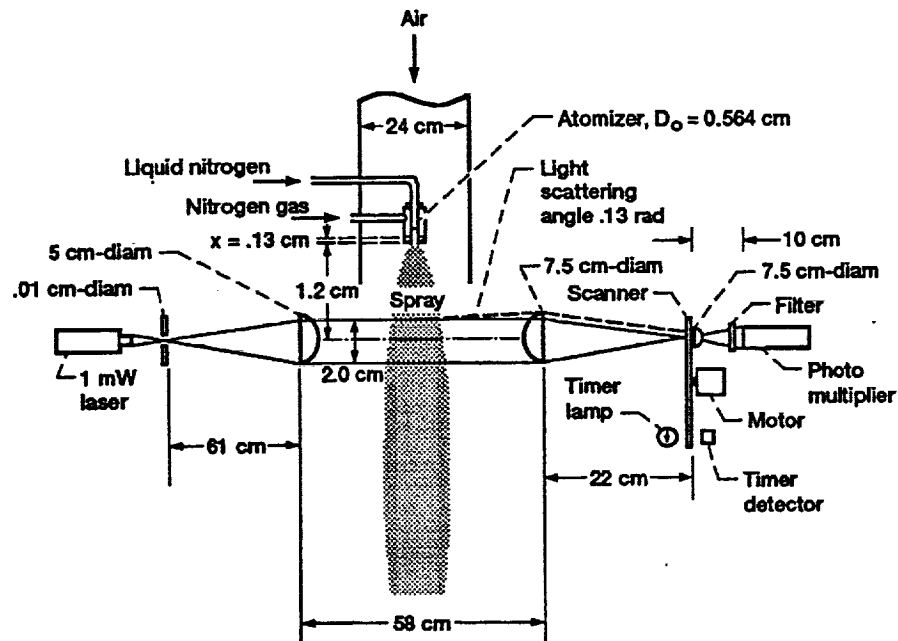


Figure 3.—Atmospheric pressure test section and optical path of scattered-light scanner.

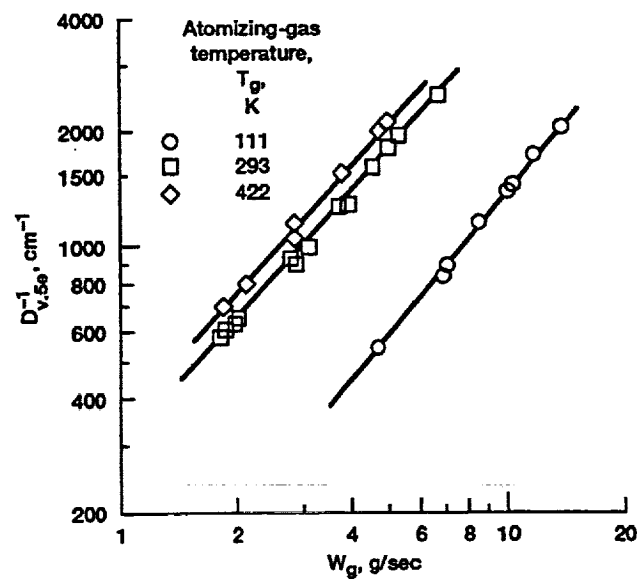


Figure 4.—Effect of atomizing-gas flowrate on reciprocal volume-median diameter,  $D_{v,5e}^{-1}$ , for partially vaporized  $\text{LN}_2$  sprays.

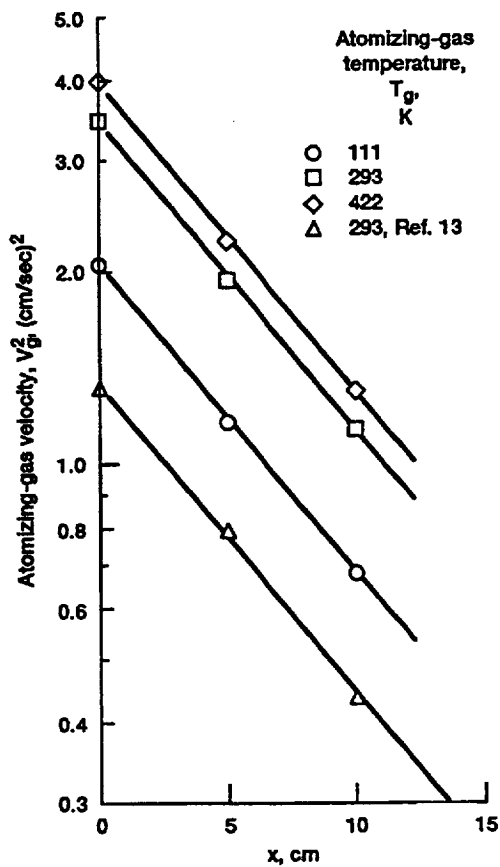


Figure 5.—Deceleration of atomizing-gas,  $\text{GN}_2$ , downstream of fuel-nozzle orifice.

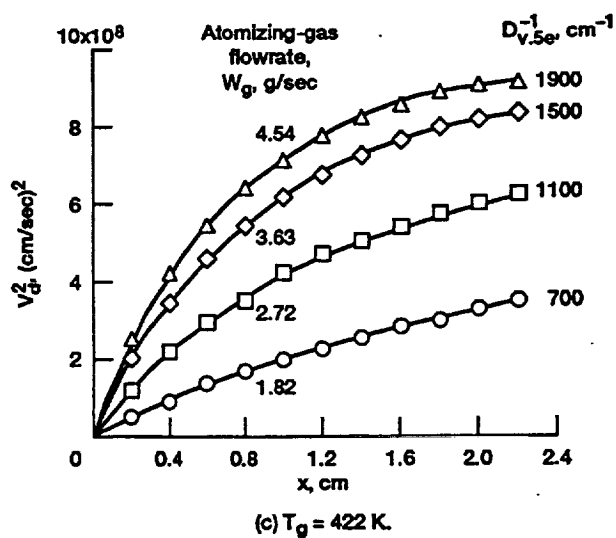
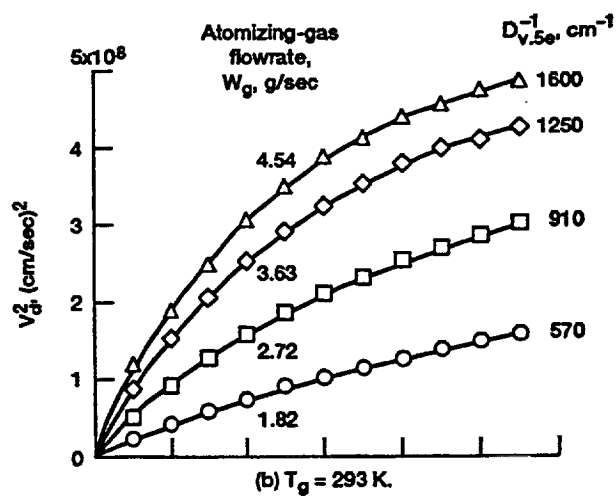
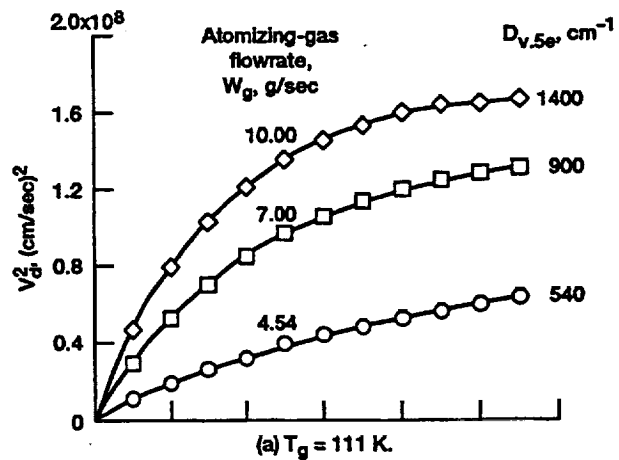


Figure 6.—Acceleration of volume-median dropsizes,  $D_{v,5e}$ .

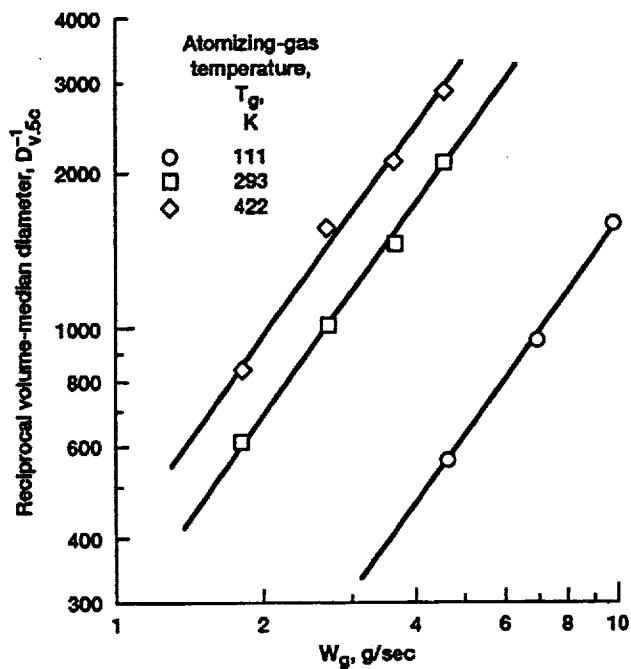


Figure 7.—Calculated effect of  $W_g$  on initial unvaporized value of  $D_{v,5c}$ , at fuel nozzle orifice,  $x = 0$ .

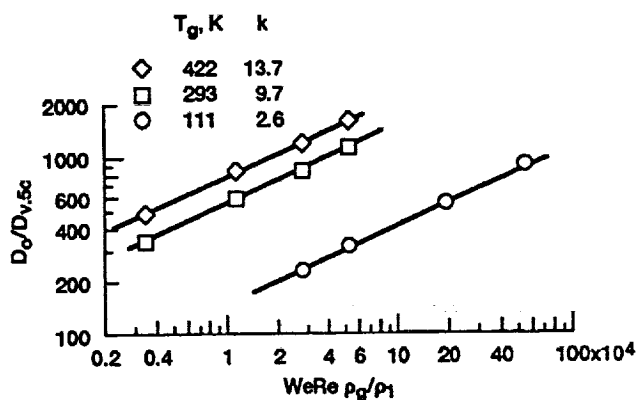


Figure 8.—Correlation of  $D_o/D_{v,5c}$  with dimensionless groups.

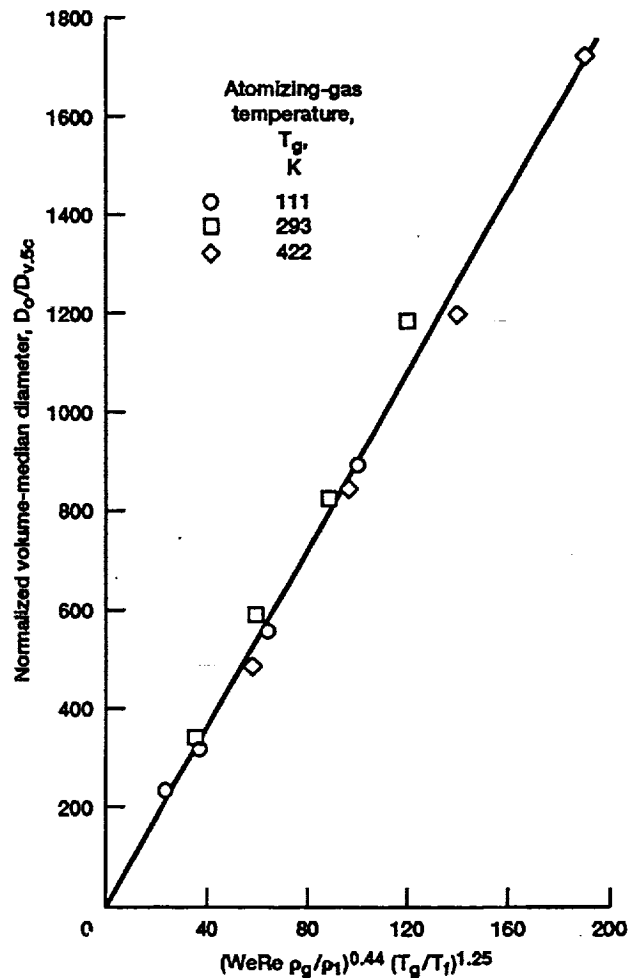


Figure 9.—Correlation of  $D_o/D_{v,5c}$  with dimensionless groups.



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13. ABSTRACT (Maximum 200 words)  Correlating expressions for two-phase flow breakup of liquid nitrogen, LN <sub>2</sub> , jets in sonic velocity nitrogen gasflows were obtained for an atomizing-gas temperature range of 111 to 442K. The correlations were based on characteristic dropsizes measurements obtained with a scattered-light scanner. The effect of droplet vaporization on the measurements of the volume-median dropsizes, $D_{v,5}$ , was calculated by using previously determined heat and momentum transfer expressions for droplets evaporating in high-velocity gasflow. Finally, the dropsizes of the originally unvaporized spray, $D_{v,5c}$ , was calculated, normalized with respect to jet diameter, $D_o$ , and correlated with atomizing-gas flowrate and temperature, according to the following expression:  $D_o/D_{v,5c} = 9.0 (WeRe \rho_g/\rho_l)^{0.44} (T_g/T_o)^{1.25}$  where $WeRe = \rho_g D_o^2 V_o^3 / \mu_l \sigma$ . Here $\mu_l$ is liquid viscosity, $\rho_g$ and $\rho_l$ are gas and liquid densities, respectively, $\sigma$ is surface tension, $V_o$ is acoustic gas velocity and $T_g$ is atomizing-gas temperature, normalized with respect to airstream temperature, $T_o = 293$ K. This expression agrees well with atomization theory which predicts $D_{v,5} \sim V_o^{1.33}$ , for liquid-jet breakup in high-velocity gasflow.				
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